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REAL-TIME COMPUTATIONS OF PILOT BALLOON WINDS

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and
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WHITE SANDS MISSILE RANGE, NEW MEXICO

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ABSTRACT

This report shows that the mean wind through a given altitude layer can be determined from balloon tracking data without computing wind values for individual points within the altitude layer. The assumptions involved in the procedure are similar to the assumption made in numerical differentiating techniques, i.e., the position can be approximated by a polynomial.

Two such techniques are investigated. One uses a linear equation to approximate the position; the other uses a cubic equation. These techniques were applied to balloon data from 27 balloon tracks and compared with results obtained from numerical differentiation. It is shown that there is very little difference among the results of the various calculation procedures.

CONTENTS

INTRODUCTION

Standard techniques for wind measurements above the level at which a fixed instrument (anemometer) is feasible employ the use of balloons. As the balloon ascends, its position is tracked by theodolites, radar, or GMD. The tracking data are processed to obtain the position of the balloon at discrete time periods.

To determine the wind velocity, one usually numerically differentiates the position data and assumes that the horizontal component of the wind is equal (at least in magnitude) to the horizontal component of the balloon's velocity. The degree of sophistication involved in the numerical differentiation technique depends upon the frequency, amount of data, and the accuracy desired. Once one has obtained wind velocities at various altitudes, the mean wind through a given altitude layer can be computed as a simple average. This paper presents and evaluates a simple technique for calculating the mean wind through an altitude layer, which does not require the computation of the individual wind velocities. This procedure is well suited for real-time computer applications wherein the available computation time is limited.

A real-time meteorological system has been developed by the Atmospheric Sciences Laboratory, White Sands Missile Range (WSMR), New Mexico, for support of unguided rocket firings (Duncan and Rachele, 1967); this system uses pilot balloons for wind measurements from 150 to 3000 meters. The balloons are tracked by either radar or a semiautomatic triple theodolite system. The system is currently used for support of the Athena rocket and will also be used for support of the Aerobee 350 rocket firings.

The techniques presented here are used for real-time system wind calculations. Therefore, it is of interest to know not only estimates of the errors in the computed winds but also the contribution of these errors to the impact dispersion of the rocket. Both problems will be analyzed. It must be emphasized that this paper considers only those errors introduced by the calculation procedures and does not attempt to consider errors in the tracking system.

DISCUSSION

Let (X, Y, Z) be a right-handed orthogonal topocentric system with the positive Z axis vertical (i.e., along the outward normal to

the earth). The motion of the balloon can be expressed by the functional relationship f(t). The component motions are expressed functionally by

$$x = X(t)$$
$$y = Y(t)$$
$$z = Z(t)$$

Since f(t) represents the motion of a physical body, it is continuous and differentiable almost everywhere. It follows that X(t), Y(t) and Z(t) are continuous and differentiable almost everywhere. It will be assumed for convenience that Z(t) is a monotone nondecreasing function of t.

The computation of the X component of the mean wind through a given altitude layer $[Z(t_1), Z(t_2)]$ is equivalent to the computation of $\bar{\dot{X}}(t)$ for $t_1 \leq t \leq t_2$. This mean, which will be denoted by W_x, is

$$W_x = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \dot{X}(t)dt = \frac{(X(t_2) - X(t_1))}{t_2 - t_1} \tag{1}$$

Thus, if one can determine the functions X(t), Y(t), and Z(t), it is a simple matter to compute the mean wind speed for a given altitude layer. Unfortunately it is extremely difficult, if not impossible, to determine these functions. This suggests the determination of an approximating function. The standard technique is to choose a polynomial of degree n as the approximating function and determine the coefficients of the polynomial by a curve-fitting technique. When the computations are to be used in real-time applications, it is desirable to choose n as small as accuracy requirements will allow. Polynomials of degree less than or equal to 4 will be considered herein.

In the remainder of the discussion it will be assumed that the observations are equally spaced timewise. It will also be assumed that $\Delta t = 1$ and $t_1 = -t_2$. This latter assumption is nonrestrictive since it results from a simple change of variable. Consider the polynomial of degree n

$$X(t) = A_n t^n + A_{n-1} t^{n-1} + \text{------} + A_1 t + A_0. \tag{2}$$

Equation (1) yields

$$W_x = A_1 \qquad \text{for } n = 1, 2$$

$$W_x = A_3 t_1^2 + A_1 \qquad \text{for } n = 3 \text{ or } 4. \tag{3}$$

The coefficients in equations (3) can be determined by least-squares techniques. Substitution of the values so obtained into (3), after considerable simplification, yields

$$W_x = 12 \sum tx/(N(N^2 - 1)) \qquad \text{for } n = 1,\ 2 \tag{4}$$

$$W_x = \frac{10(3N^3 - 15N^2 + N + 51)\ \Sigma tx}{N(N^2-1)(N+2)(9-N^2)} + \frac{280\Sigma t^3 x}{N(N^2-1)(N+2)(N+3)} \tag{5}$$

for $n = 3,\ 4$

where N is the number of sample points in the layer, and the summations extend over the interval.

The calculations required for $n = 1$ or 2 are quite simple, especially when compared to that required for the $n = 3$ or 4 case.

EMPIRICAL EVALUATION OF THE MEAN WINDS

The errors associated with equations (4) and (5) can be evaluated theoretically by assuming various functional forms for the balloon path. However, the magnitude of the number of conceivable paths suggests that empirical evaluations may be more feasible. Toward this end, 27 100-gram pilot balloon tracks were evaluated. The balloons were tracked by a Contraves cinetheodolite system. The reduced data consisted of position and velocity data computed at the rate of one sample point per second. The velocity components were computed by a numerical differentiation technique described by Comstock et al. (1964). The average velocities (denoted U_x, U_y) were used as a basis for the comparisons.

The 27 balloon soundings were separated into two groups. In the first group, consisting of 15 soundings, equations (4) and (5) and their analogs for the y component were evaluated for adjacent height layers of 150 meters. Adjacent height layers of 60 meters were used for the data in the second group. The results for the x component are denoted W_{x_1} and W_{x_2} respectively. The wind profiles resulting from the three calculation procedures, for a typical balloon track, are shown in Figure 1. It is easy to see that the differences between any two of these wind profiles are quite small.

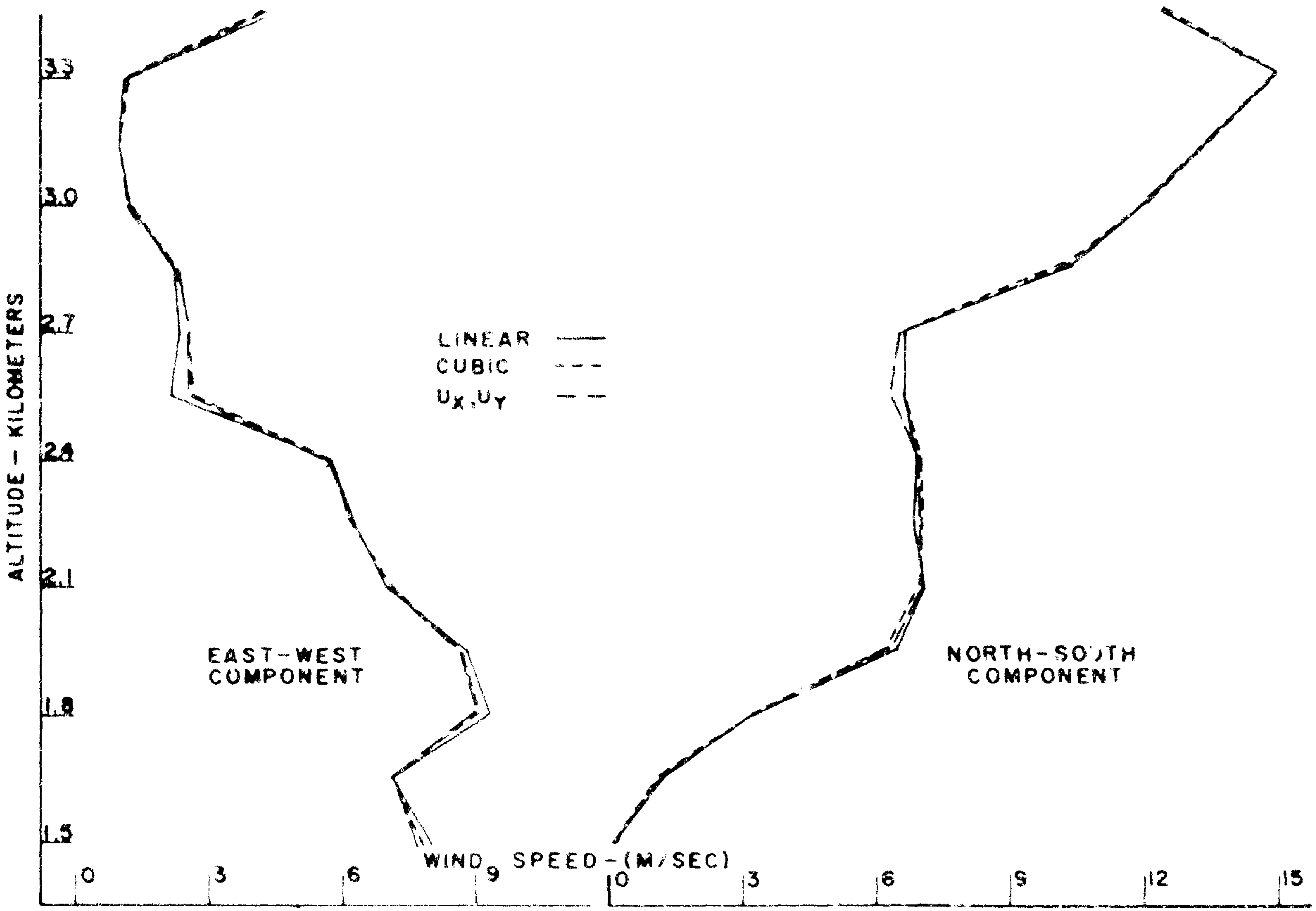

FIG. I THE THREE PROFILES FOR RUN NUMBER 15

The differences $\Delta x_1 = W_{x_1} - U_x$, $\Delta x_2 = W_{x_2} - U_x$, and $\Delta x_3 = W_{x_1} - W_{x_2}$ and their analogs for the y-component were computed for each point. These data were used to compute RMS values $\sigma_{\Delta x_1}$, $\sigma_{\Delta x_2}$, $\sigma_{\Delta x_3}$, $\sigma_{\Delta y_1}$, $\sigma_{\Delta y_2}$, and $\sigma_{\Delta y_3}$ for each balloon track; ensemble values were computed for the group I data and the group II data. These results are listed in Table I.

APPLICATION TO ROCKET IMPACT PREDICTION

Since the winds computed by equations (4) or (5) are used for rocket impact prediction, it is natural to investigate the contribution of these errors to the error in the predicted rocket impact. Although this question cannot be answered in general, it can be investigated for specific rocket configurations. Such investigations should provide insight toward the answer for other rockets of similar ballistic characteristics.

The rocket impact dispersion (change in impact from nominal), for a given wind profile, can be computed by rocket trajectory simulation [Cochran et al., 1966]. The rocket impact dispersion for each of the wind profiles discussed in the preceding section was computed. Two different rockets were considered: the Aerobee 150, a high-altitude research rocket; and the Athena, a reentry research rocket. These results are listed in Tables II and III.

CONCLUSIONS

Techniques for computing wind velocities from pilot balloon data have been presented and compared. Three methods were discussed: (1) a least-squares linear fit to the position data; (2) a least-squares cubic fit; and (3) averaging of point by point results of numerical differentiation.

The three techniques were compared by applying each computation to 27 different balloon tracks. The results for one such track, which

is considered typical, are shown in Figure 1. It is easy to see that there is very little difference among the three wind profiles. The RMS values presented in Table I also indicate that the three computational procedures yield small differences among the resulting wind profiles.

The various wind profiles were used to compute the impact dispersion of the Aerobee and Athena rockets. The results are shown in TablesII and III. The differences among the three wind profiles are considered to be quite small, especially when compared with such contributors to dispersion as thrust misalignment, wind variability, etc.

The authors contend that the differences among the three computational procedures are insignificant. This is especially true if the computed wind data are to be used for rocket impact prediction. Any of the three techniques may be applied; however, simplicity of the calculations suggests the linear fit, and this method is recommended for use in real-time rocket impact prediction.

TABLE I: RMS Differences, Meters Per Sec.

Run No.	$\sigma_{\Delta x_1}$	$\sigma_{\Delta x_2}$	$\sigma_{\Delta x_3}$	$\sigma_{\Delta y_1}$	$\sigma_{\Delta y_2}$	$\sigma_{\Delta y_3}$
I 1	0.18	0.21	0.19	0.16	0.24	0.17
I 2	0.11	0.10	0.17	0.11	0.07	0.13
I 3	0.14	0.18	0.19	0.23	0.10	0.21
I 4	0.17	0.11	0.18	0.17	0.12	0.19
I 5	0.18	0.08	0.19	0.12	0.10	0.14
I 6	0.14	0.10	0.19	0.20	0.16	0.20
I 7	0.20	0.13	0.24	0.19	0.17	0.16
I 8	0.25	0.13	0.25	0.33	0.17	0.42
I 9	0.09	0.08	0.12	0.14	0.07	0.16
I 10	0.19	0.23	0.19	0.25	0.18	0.27
I 11	0.16	0.13	0.22	0.11	0.09	0.14
I 12	0.10	0.05	0.14	0.11	0.07	0.09
I 13	0.11	0.07	0.17	0.17	0.10	0.14
I 14	0.19	0.18	0.14	0.07	0.09	0.10
I 15	0.17	0.10	0.20	0.14	0.07	0.18
I*	0.15	0.11	0.18	0.16	0.10	0.17
II 1	0.14	0.08	0.16	0.10	0.06	0.12
II 2	0.28	0.24	0.31	0.36	0.31	0.30
II 3	0.52	0.39	0.31	0.40	0.35	0.24
II 4	0.33	0.20	0.32	0.42	0.33	0.30
II 5	0.23	0.23	0.19	0.20	0.22	0.15
II 6	0.21	0.18	0.16	0.16	0.13	0.13
II 7	0.35	0.25	0.22	0.24	0.14	0.21
II 8	0.16	0.13	0.15	0.13	0.14	0.14
II 9	0.27	0.17	0.22	0.26	0.22	0.25
II 10	0.13	0.06	0.18	0.09	0.06	0.13
II 11	0.23	0.18	0.29	0.26	0.29	0.26
II 12	0.27	0.21	0.21	0.25	0.17	0.20
II*	0.28	0.22	0.23	0.26	0.23	0.22

* Ensemble Estimates.

TABLE II: AEROBEE IMPACT DISPERSION FOR DIFFERENT WIND PROFILES

	X-Component Meters			Y-Component Meters		
	Profile	Profile	Profile	Profile	Profile	Profile
Run No	W_{x_1}	W_{x_2}	U_x	W_{y_1}	W_{y_2}	U_y
I 1	14064.	14236.	14593.	4851.	5145.	5275.
I 2	35761.	36486.	35282.	33174.	33831.	33007.
I 3	31116.	31431.	31350.	27778.	28098.	28122.
I 4	33499.	33509.	33373.	33210.	32624.	32709.
I 5	32618.	32582.	32660.	31592.	31425.	31259.
I 6	-8136.	-7601.	-7766.	51649.	51847.	52465.
I 7	-3983.	-3501.	-3726.	50845.	50958.	50097.
I 8	-5282.	-4715.	-4493.	50586.	52291.	51424.
I 9	7081.	7060.	6962.	46872.	47202.	47072.
I 10	-6012.	-5895.	-5887.	47710.	47683.	47072.
I 11	21525.	21605.	22320.	-2742.	-2235.	-2436.
I 12	27367.	27119.	27208.	-1675.	-1340.	-1283.
I 13	24589.	25619.	25366.	-3052.	-2769.	-2265.
I 14	18056.	18370.	17933.	-7516.	-8036.	-7549.
I 15	24870.	24094.	24326.	-5772.	-5753.	-5759.
II 1	5783.	4921.	5482.	1241.	930.	1350.
II 2	-[illegible]240.	-2933.	-3125.	80445.	80877.	81326.
II 3	-8078.	-7457.	-7973.	74986.	75323.	74445.
II 4	-16415.	-15662.	-15304.	82375.	81500.	82586.
II [illegible]	12569.	14533.	14873.	68361.	68203.	677[illegible].
II 6	-1911.	-2004.	-2009.	72171.	71559.	71346.
II 7	16285.	19460.	21791.	-7429.	-5936.	-4310.
II 8	29869.	30494.	30871.	875.	854.	1059.
II 9	22481.	23014.	24752.	-663.	-3526.	-3007.
II 10	16810.	17568.	16908.	-7988.	-6136.	-5210.
II 11	32996.	30568.	31087.	-3025.	-3213.	-6156.
II 12	56423.	57807.	58645.	35628.	35185.	34270.

TABLE III: ATHENA IMPACT DISPERSION FOR DIFFERENT WIND PROFILES

Run No.	X-COMPONENT Meters Profile W_{x_1}	Profile W_{x_2}	Profile U_x	Y-COMPONENT Meters Profile W_{y_1}	Profile W_{y_2}	Profile U_y
I 1	28391.	28973.	30055.	-5404.	-5213.	-4913.
I 2	126142.	127792.	126304.	14580.	14509.	14305.
I 3	121369.	122123.	121209.	13358.	13449.	13434.
I 4	121030.	120757.	120077.	15589.	15059.	15327.
I 5	126823.	126182.	126308.	15541.	15566.	15503.
I 6	-23840.	-22386.	-22769.	33047.	33080.	32914.
I 7	-14813.	-12819.	-13376.	33780.	33864.	33987.
I 8	-13842.	-12849.	-12849.	34850.	34787.	34787.
I 9	28215.	28501.	27772.	33496.	33489.	33501.
I 10	-18920.	-18251.	-18229.	33659.	33117.	33658.
I 11	64929.	63475.	66899.	-10597.	-9483.	-9920.
I 12	79920.	79194.	79645.	-12164.	-11418.	-11356.
I 13	66594.	71107.	70173.	-12800.	-12589.	-11922.
I 14	51335.	51019.	50027.	-14836.	-14842.	-14280.
I 15	67613.	65248.	65985.	-11759.	-11654.	-11676.
II 1	28104.	26432.	25518.	-5772.	-5901.	-5504.
II 2	-23608.	-22233.	-21981.	31658.	31828.	31797.
II 3	-8901.	-9312.	-11172.	33680.	33677.	33656.
II 4	-16417.	-15764.	-16150.	33619.	33649.	33540.
II 5	25353.	28095.	29691.	33600.	33474.	33488.
II 6	-16931.	-17374.	-17981.	33603.	33588.	33621.
II 7	60775.	65983.	67159.	-9142.	-9647.	-8979.
II 8	80881.	81534.	81828.	-10575.	-10893.	-10790.
II 9	63144.	65977.	68825.	-8959.	-11350.	-11522.
II 10	45815.	46180.	45013.	-15129.	-14535.	-13984.
II 11	71199.	67314.	67214.	-11277.	-12252.	-12665.
II 12	156728.	156835.	156934.	9673.	9671.	9809.

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13. ABSTRACT

This report shows that the mean wind through a given altitude layer can be determined from balloon tracking data without computing wind values for individual points within the altitude layer. The assumptions involved in the procedure are similar to the assumption made in numerical differentiating techniques, i.e., the position can be approximated by a polynomial. Two such techniques are investigated. One uses a linear equation to approximate the position; the other uses a cubic equation. These techniques were applied to balloon data from 27 balloon tracks and compared with results obtained from numerical differentiation. It is shown that there is very little difference among the results of the various calculation procedures.

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